

# On the Velocity of the Cathode Rays Ejected by Substances Exposed to the $\gamma$ -Rays of Radium

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*On the Velocity of the Cathode Rays ejected by Substances exposed to the  $\gamma$ -Rays of Radium.*

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§ I.

The cathode radiation from a substance exposed to the  $\gamma$ -rays of radium consists, as is well known, partly of rays of a very penetrating character. Thus Eve found that the secondary rays from a lead plate, which in his experiments were deflected by a strong magnet into an ionisation chamber, possessed approximately the same penetrating power as the  $\beta$ -rays of uranium. He tested the penetrating power of these deflected rays by placing successively different thicknesses of aluminium foil over the opening of the chamber and measuring the changes produced in the leak.

This paper gives an account of some experiments of a more elaborate character by the writer on the subject. Two different methods were used in these experiments. One of the methods consisted in measuring the scattering of the cathode particles produced by different thicknesses of metal foil placed in the path of the rays. In the other method the cathode rays were deflected into an ionisation chamber by means of a strong electromagnet, and the ionisation in the chamber measured for magnetic fields of different strengths.

It will be then seen that each method has its particular advantages in bringing out the different properties of the secondary radiation.

The form of apparatus used in the first method is shown in fig. 1. A is an aluminium ionisation chamber 12·5 cm. long, 10 cm. high, and 7 cm. deep, supported by a wooden frame arrangement from which it was insulated. The metal plate B resting on the adjustable table C formed the lower side of the chamber. The plate could be removed and replaced by another after lowering the table a convenient distance from the chamber. Thirty milligrammes of radium bromide (enclosed in a glass tube) were placed in the cavity of the lead cylinder D, and a piece of sheet lead 3 mm. thick placed over the opening of the cavity to cut off the  $\beta$ -rays. E is another ionisation chamber whose electrode was connected with that of the chamber A. One of the chambers was connected to a positive potential of 200 volts and the

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other chamber to a negative potential of 200 volts. The ionisation in both chambers was produced by the  $\gamma$ -rays from the radium, the amount of ionisation in the chamber E being regulated by screens of different thicknesses placed between the radium and the chamber. The object of the chamber E was to partially compensate by means of its leak that part of the leak in the chamber A which is not due to the cathode rays from the plate B.

The penetrating power of the secondary cathode rays emitted by the plate B was investigated by measuring the ionisation in the chamber for different thicknesses of aluminium or paper foil placed upon the plate. If the radiation from the foil is small in comparison with the radiation from

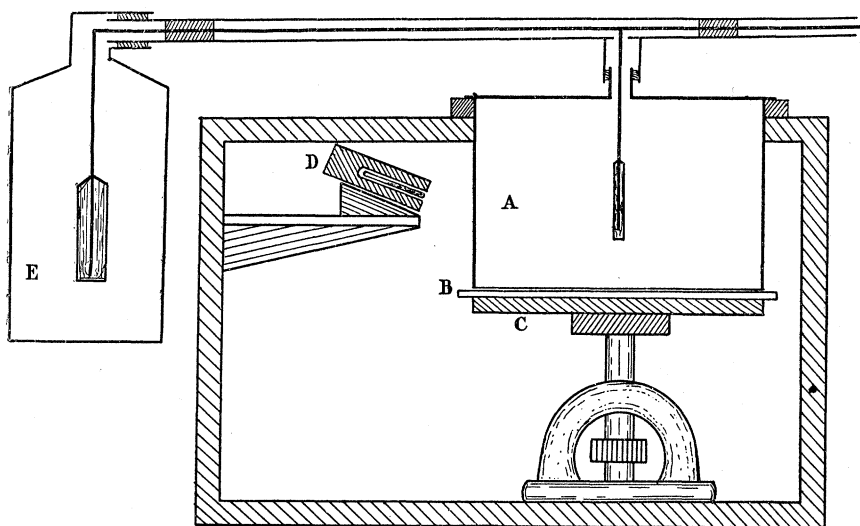


FIG. 1.

another sheet of foil of the same mass per  $\text{cm}^2$ , but of the material of the plate B, the secondary radiation from a combination of the plate B and a sheet of foil is the radiation from the plate modified by the scattering of the foil. The coefficient of absorption of the foil is in that case easily obtained. Thus, let  $M$  denote the leak in the chamber A produced by the secondary cathode radiation from the plate B, and  $N$  the remaining leak in the chamber minus the leak in the chamber E. The leak obtained when there is no foil on the plate is then  $(M+N)$ . When a sheet of foil is placed on the plate the leak obtained is  $(\phi M+N)$ , where  $\phi$  denotes the fraction of the secondary radiation from the plate which penetrates the foil. If an additional sheet of foil of the same thickness is placed on the plate, the leak obtained is  $(\phi^2 M+N)$ . The difference between the first and third

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leak divided by the difference between the first and second then gives the value of  $(1-\phi^2)/(1-\phi)$ , that is of  $(\phi+1)$ . And if  $x$  denotes the thickness and  $\lambda$  the coefficient of absorption of the foil, we have  $e^{-x\lambda} = \phi$ , from which  $\lambda$  can be obtained.

The value of  $\phi$ , we have seen, gives the fraction of the amount of radiation from the plate which penetrates a given thickness of foil. But this applies only to the whole radiation from the plate if it is homogeneous. If the radiation is heterogeneous, the value of  $\phi$  applies only to that part of the radiation which is easily absorbed in comparison with the remaining part. This follows from the particular way in which  $\phi$  is obtained. Thus, let the radiation from the plate be divided into two parts, A and B, and let the values of  $\phi$  for the two parts be  $\phi_1$  and  $\phi_2$  respectively. The difference between the leak with a sheet of foil on the radiating plate and the leak without the foil is then  $A(1-\phi_1) + B(1-\phi_2)$ . Now, we may suppose the radiation divided into two parts, such that  $(1-\phi_2)$  is so small that  $B(1-\phi_2)$  is negligible in comparison with  $A(1-\phi_1)$ . The difference between the leak with two sheets of foil and the leak without foil is then  $A(1-\phi_1^2)$ , and the ratio of this difference to the other difference equal to  $(1+\phi_1)$ . Therefore if the rays are heterogeneous, the value of  $\phi$  found by the above method and the coefficient of absorption deduced therefrom applies to the set of rays A. This method thus brings the existence of the soft rays in a set of rays into evidence, and furnishes also a measure of their penetrating power.

The value obtained for  $\phi$ , it will be observed, is influenced by the secondary radiation from the foil itself, if this is not of negligible magnitude. For the radiation from the foil, when added to the part of the radiation from the plate which penetrates the foil, has the effect of making the fraction of the radiation which penetrates the foil appear larger than it really is. A smaller value for  $\lambda$  than the true value will consequently be obtained.

But by using a proper combination of plate and foil, the effect of the radiation from the foil becomes negligible. Thus, if the radiating plate is of aluminium, or of a metal of higher atomic weight than aluminium, and paper foil used to absorb the secondary rays, the effect of the radiation from the paper on the value of  $\phi$  is small. This was proved in the following manner:—The radiations from a sheet of paper and a sheet of aluminium foil were compared with one another, each sheet radiating under the same conditions as the radiating plate. The details of this experiment will be described further on. The sheets of foil were two of those used to absorb the cathode rays in these experiments; the paper foil weighed  $6.4 \times 10^{-3}$  and the aluminium foil  $9.27 \times 10^{-4}$  gramme per cm.<sup>2</sup> It was found that each of these two sheets of foil produced practically the same amount of secondary

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radiation. The radiations from aluminium and paper for equal masses per cm.<sup>2</sup> are therefore in the ratio of 1 to 0·13. Consider the effect of placing a sheet of aluminium foil on an aluminium radiating plate. It is evident that the decrease of secondary radiation from the plate due to the scattering of the foil is exactly counterbalanced by the radiation from the foil. But if a sheet of paper foil of the same mass per cm.<sup>2</sup> as the aluminium foil be placed on the plate, the radiation from the paper, according to the foregoing, would be only about 0·13 of that from the aluminium foil. But the amount of scattering produced would be the same in each case. This follows from the experiments on the scattering of cathode rays. Thus it has been shown that the amounts of scattering of aluminium and paper for equal masses per cm.<sup>2</sup> are equal to one another over a wide range of velocities of the cathode rays produced in a vacuum tube, and in the case of the  $\beta$ -rays of uranium. We may suppose, therefore, as a first approximation, that a sheet of paper foil placed on a plate of aluminium produces only scattering of the radiation from the plate.

But this must also be true if a radiator of higher atomic weight than aluminium is used. For in that case, since the radiation from equal masses increases with the atomic weight of the material, the difference between the amounts of radiation of the paper foil and an equivalent piece of foil of the same material as the radiating plate is even greater than in the foregoing case.

Further, since the ratio of the atomic weight of lead to that of aluminium is greater than the ratio of the atomic weight of aluminium to the average atomic weight of paper, this will obviously be also true in the case of aluminium foil and a lead plate.

The relative amounts of radiation from a sheet of paper and a sheet of aluminium foil were found in the following manner. The table C was removed, and a wire gauze fixed to the chamber so as to form its lower side. The leak in the chamber was then measured. A sheet of paper foil fixed to a metal frame was then placed underneath the gauze so as to be in contact with it, and the leak again measured. In the same manner a leak was obtained with a sheet of aluminium foil fixed to the frame. The first leak was then subtracted from the second and third, the result giving the amounts of radiation from the paper and aluminium foil respectively.

Table I gives the values of  $\phi$  for paper foil obtained with a number of different metals in the manner described. Each of the measurements required for calculating  $\phi$  is the mean of at least eight readings. The readings were taken in the same manner as described in a previous paper.\*

\* 'Phil. Mag.,' November, 1907, p. 619.

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The *apparent* leak was usually decreased by about 50 per cent. when a sheet of foil was placed on the plate.\*

Table I.

| Radiator and its thickness. |      | $\phi$ for paper weighing $6.4 \times 10^{-3}$ gramme per cm. <sup>2</sup> . |
|-----------------------------|------|------------------------------------------------------------------------------|
|                             | mm.  |                                                                              |
| Pb                          | 2    | 0.53                                                                         |
| Pb                          | 0.25 | 0.50                                                                         |
| Sn                          | 3    | 0.54                                                                         |
| Zn                          | 3    | 0.54                                                                         |
| Cu                          | 2.5  | 0.55                                                                         |
| Fe                          | 2.5  | 0.52                                                                         |
| Ni                          | 2.5  | 0.53                                                                         |
| S                           | 4    | 0.52                                                                         |
| Al                          | 3.5  | 0.53                                                                         |

It will be seen that the value of  $\phi$  is approximately the same for the different metals, the mean value being about 0.53. Thus part of the secondary cathode radiation from each of these plates is reduced to about one-half by a sheet of paper (weighing  $6.4 \times 10^{-3}$  gramme per cm.<sup>2</sup>) placed close to the radiating plate. If all the radiation from a plate possessed the same penetrating power as the  $\beta$ -rays from uranium, the value of  $\phi$  would be 0.99, and a single sheet of paper foil would in that case stop about 1 per cent. of the radiation. It appears, therefore, that the secondary cathode radiation from a plate on the side where the  $\gamma$ -rays enter consists partly of very absorbable rays.

The penetrating power and heterogeneity of this absorbable radiation is best brought out by considering the values of  $\phi$  and  $\lambda$  found for aluminium foil. Aluminium foil is more homogeneous than paper, and it is therefore better to use aluminium foil when possible. Table II gives the values obtained for  $\phi$  and  $\lambda$  when a radiator of lead was used. The coefficient of absorption of aluminium for the cathode rays in a vacuum tube, and for the  $\beta$ -rays of uranium oxide, are placed in the table for comparison. The first column in the table gives the nature of the source of cathode radiation. The second column contains values of  $\phi$ . The first value of  $\phi$  given corresponds to the soft secondary rays from a lead plate exposed to  $\gamma$ -rays, and the second to those rays which penetrated a layer of aluminium leaf weighing  $2.72 \times 10^{-3}$  gramme per cm.<sup>2</sup> placed upon the plate. The third column gives the values of  $\lambda$  for the different cathode rays.

It will be seen that the coefficient of absorption of aluminium for the soft

\* The paper was blackened with graphite in order to make it a good conductor of electricity.

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cathode rays from the lead plate is very much greater than that found for the  $\beta$ -rays of uranium, but smaller than that found by Lenard for the cathode rays in a vacuum tube. A comparison of these coefficients of absorption with some coefficients of absorption and corresponding velocities

Table II.

| Nature of the source of cathode radiation.                                                                                                                                                 | $\phi$ for aluminium leaf weighing $9.27 \times 10^{-4}$ gramme per cm. <sup>2</sup> Calculated thickness of leaf, $3.4 \times 10^{-6}$ cm. Equivalent in mass to a thickness 0.72 cm. of air. | $\lambda$ . |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| Secondary cathode rays from a plate exposed to the $\gamma$ -rays of radium.                                                                                                               | 0.52                                                                                                                                                                                           | 1898        |
| The secondary cathode rays from the lead plate passed through aluminium leaf weighing $2.72 \times 10^{-3}$ gramme per cm. <sup>2</sup> Equivalent in mass to a thickness of 2 cm. of air. | 0.804                                                                                                                                                                                          | 640         |
| Cathode rays in a vacuum tube. Velocity about $6 \times 10^9$ cm./sec. (Lenard).                                                                                                           | —                                                                                                                                                                                              | 7150        |
| $\beta$ -rays from uranium (Rutherford).                                                                                                                                                   | —                                                                                                                                                                                              | 14          |

given by Lenard,\* suggests that the velocity of these soft secondary rays, on the supposition that they are homogeneous, is about twice that of the cathode rays in a vacuum tube and one-third that of the  $\beta$ -rays of uranium. But the rays are not homogeneous, as will be shown presently, and the velocities therefore range above and below this value.

Next let us consider the values of  $\phi$ , which, it will be remembered, denote the fractions of the soft cathode radiations penetrating a piece of foil of a given thickness. Thus aluminium foil  $3.4 \times 10^{-6}$  cm. thick reduces the soft radiation from a lead plate to 0.5 of its original value. The sheet of foil is equivalent in mass to a layer of air 0.72 cm. thick. Therefore, if we assume that the absorption of the rays by air and aluminium is the same for equal masses per cm.<sup>2</sup>, half of this soft radiation is absorbed in the 0.72 cm. of air adjacent to the plate.

When the cathode rays were first sifted through an aluminium layer weighing  $2.72 \times 10^{-3}$  gramme per cm., the value obtained for  $\phi$  was 0.82, which is a larger value than that obtained without previous sifting. The radiation which penetrated the aluminium layer did not, therefore, contain as large an amount of soft radiation as the whole radiation from the plate.

\* See 'Conduction of Electricity through Gases,' by Prof. J. J. Thomson, second edition, p. 381.

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Some of the soft rays were, therefore, completely absorbed by the aluminium layer. And since the layer is equivalent in mass to about 2 cm. of air, some of the cathode rays from the plate were *completely* absorbed in the 2 cm. of air adjacent to the plate.

The radiation which penetrated the aluminium layer contained much less soft radiation than the whole radiation from the plate. Thus about 0.5 of the whole radiation from the plate was absorbed by a sheet of aluminium foil  $3.4 \times 10^{-4}$  cm. thick, while only (1-0.82) or 0.18 of the radiation which penetrated the aluminium layer was absorbed by the same sheet of foil.

The foregoing considerations show that the soft rays from a plate are heterogeneous. They also show that the coefficients of absorption found apply principally to those cathode rays which have a range of 1 or 2 cm. only. The properties of these soft rays were brought into prominence not only by the particular method of investigation adopted, but also by using very thin sheets of absorbing material. For if a heterogeneous beam of cathode rays is gradually cut down by successive pieces of thin foil, the decrease will be more rapid at the beginning on account of the absorbable radiation being more rapidly absorbed than the more penetrating. The coefficient of absorption obtained with thin foil will therefore be larger than that obtained with foil which is much thicker, and thin foil therefore brings out the properties of the soft radiation to a greater extent than thick foil.

Table I shows that the value of  $\phi$  for a given thickness of paper foil is independent of the nature of the radiating plate. Thus the nature or penetrating power of the soft radiation in question is independent of the nature of the radiating material. It does not follow, however, that this result must also be true for the penetrating radiation emitted by the plate. It is probable that the penetrating cathode radiation set free in a plate is successively transformed into other radiations of less and less penetrating power, the radiation ultimately produced from all materials being  $\delta$ -rays, which, in their turn, do not produce any secondary radiation. The soft secondary radiation from a plate produced in that way would be practically independent of the nature of the radiating plate. It seems, therefore, that the soft radiation is largely produced by the penetrating  $\beta$ -rays ejected by the  $\gamma$ -rays. Other experiments seem to point to the same conclusion.

Thus it was found that the nature of the cathode rays is practically independent of previous sifting of the  $\gamma$ -rays through a thick screen of metal. This result is shown by Table III. The soft radiation is, therefore, not produced by very absorbable rays in the beam of  $\gamma$ -rays, for previous sifting of the beam would diminish the very absorbable rays in a greater

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proportion than the more penetrating rays, and the penetrating power of the secondary cathode radiation would thereby be increased.

Table III.

|                                 |                   |
|---------------------------------|-------------------|
| Lead screen 1·3 cm. thick ..... | $\phi = 0\cdot50$ |
| Zinc screen 2·0 cm. thick ..... | $\phi = 0\cdot50$ |
| Lead screen 0·3 cm. thick ..... | $\phi = 0\cdot53$ |

Very little of the soft cathode radiation seems to be produced by the soft  $\gamma$ -rays generated in the plate, for the penetrating power of the radiation is practically independent of the thickness of the radiating plate. Thus the values of  $\phi$  in Table I for two lead radiators, one of which was 0·25 and the other 2 mm. thick, were 0·50 and 0·53 respectively. Some of the radiation must, however, be produced by the secondary  $\gamma$ -rays, since secondary  $\gamma$ -rays are produced in a substance exposed to  $\gamma$ -rays, which are so soft as to be almost entirely absorbed by the substance.\* It may be mentioned in passing that there is some indirect evidence that such soft  $\gamma$ -rays are likely to be produced. Thus Barkla† found that the secondary X-radiation from carbon becomes softer in comparison with the primary X-rays as the hardness of the primary rays is increased.

The soft cathode radiation possesses considerable ionising power, since the leaks were not appreciably altered by reversing the sign of all the potentials. If the leaks consisted largely of cathode particles which originated in the plate, the magnitude of the leaks would have been considerably decreased when the potential of the chamber was changed from positive to negative.

The foregoing method may also be used to investigate the penetrating power of the soft radiation on the side of the plate where the  $\gamma$ -rays emerge. But in this case the radiations from two sheets of foil of equal mass but of different materials do not differ so much from one another as in the foregoing case. This is due to the fact that the radiation from the side of a plate where the  $\gamma$ -rays emerge does not decrease so rapidly with decrease of atomic weight of the plate as the radiation from the other side. This effect was explained by Prof. Bragg and Dr. Madsen by supposing that the secondary cathode rays are initially projected in the direction of propagation of the  $\gamma$ -rays.‡ The value of  $\phi$  obtained by this method will therefore be larger than the true value; but still the results with this restriction will be seen to be of importance.

\* Kleeman, 'Phil. Mag.,' May, 1908, p. 638.

† Barkla, 'Phil. Mag.,' February, 1908, p. 288.

‡ 'Phil. Mag.,' May, 1908, p. 663.

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The experiments in this case were carried out in the following manner. The adjustable table was moved to one side of the chamber, and the radiating plate held in position by two arms attached to the table. The radium was placed underneath the plate at a distance of about 9 cm. from its centre. Readings with foil were then taken in the same way as before.

The values found for  $\phi$  for aluminium and paper foil when a lead radiator was used were 0.45 and 0.16 respectively. These values are smaller than those found under previous conditions, viz., 0.52 and 0.53 respectively. The difference is greater with paper than with aluminium foil, this being probably due to the radiation from the paper foil affecting the value of  $\phi$  to a less extent than the radiation from the aluminium foil. The radiation from the foil, we have seen, affects the values of  $\phi$  for the side where the  $\gamma$ -rays emerge to a greater extent than the values for the other side. And since the effect of the radiation is to make  $\phi$  greater than its true value, the difference between the values for the two sides of the plate must be even greater than those given by the above values. It appears, therefore, that the soft radiation on the side of the plate where the  $\gamma$ -rays emerge is considerably softer than that on the other side.

This is an interesting result; but the true explanation is not at all clear. One way of explaining it is as follows.

The soft radiation, we have seen, is to a large extent produced by the cathode rays projected by the  $\gamma$ -rays. Since the cathode rays produced by the  $\gamma$ -rays are projected in the direction of propagation of the rays, it is not improbable, on the æther-pulse theory, that a  $\gamma$ -ray deflects in the direction of its propagation the soft cathode radiation over which it may happen to pass. This may take place principally in the following way.

A  $\gamma$ -pulse is probably followed by a number of pulses of much less intensity produced by the same electron as the principal pulse, and also by secondary pulses produced in the matter which it traverses. These pulses will pass over the cathode ray produced by the  $\gamma$ -pulse, since they are all (for a time at least) moving in the same direction. The soft radiation produced by the cathode ray might, therefore, be to some extent deflected in the direction of propagation of the pulses.

It is not improbable, however, that this is not the true explanation of the effect. Further investigations on secondary radiation and scattering of cathode rays will probably make this clear.

Some experiments were also made on the soft radiation produced by the  $\beta$ - and  $\gamma$ -rays together on the emergent side of a plate. The radiating plate was a sheet of lead 0.25 mm. thick, stretched over a frame. The radium was placed underneath the plate in the same position as in the experiments just

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described. It was not covered by a screen, and some of the  $\beta$ -rays which penetrated the glass tube therefore penetrated in part the lead sheet. The soft cathode radiation produced was therefore due to the action of the  $\beta$ - and  $\gamma$ -rays.

The values of  $\phi$  for aluminium and paper foil obtained with this arrangement were 0.57 and 0.29 respectively. These values are larger than those obtained with a lead plate 2 mm. thick, and with the  $\beta$ -rays cut off by a screen, viz., 0.45 and 0.16 respectively. It appears, therefore, that the soft radiation produced by the  $\beta$ - and  $\gamma$ -rays together is of a more penetrating character than that produced by the  $\gamma$ -rays alone. This is probably due, considering the way  $\phi$  was obtained, to the  $\beta$ -radiation produced by the  $\gamma$ -rays being more heterogeneous than the  $\beta$ -rays of radium after having passed through the walls of a glass tube and a sheet of lead. And the less penetrating radiation was therefore smaller in comparison with the remaining radiation when both the  $\beta$ - and  $\gamma$ -rays were used, than when the  $\gamma$ -rays alone were used. It would appear afterwards, from the magnetic deflection experiments, that the  $\beta$ -rays ejected by the  $\gamma$ -rays are heterogeneous—that is, have different velocities.

Table IV gives some values of  $\phi$  obtained for different distances of the radium from the radiating plate. The values refer to the side of the plate where the  $\gamma$ -rays entered. It will be seen that there is practically no difference in the values obtained. The nature of the soft radiation is, therefore, as we would expect, independent of the distance of the radium from the radiating plate.

Table IV.

| Distance of radium from lead radiator. | $\phi$ . |
|----------------------------------------|----------|
| cm.                                    |          |
| 11.0                                   | 0.50     |
| 12.5                                   | 0.53     |
| 17.0                                   | 0.54     |

## § II.

The experiments in which the velocity of the cathode rays was investigated by deflecting them by a magnetic field will now be described. The form of apparatus used in these experiments is shown in fig. 2. A is an ionisation chamber; it consisted of an oblong lead box 8 cm. long, 5.5 cm. high, and 6 cm. deep. The side  $ab$  of the chamber consisted of tightly stretched tissue-paper. B and C are lead blocks which served to screen the chamber

from the direct action of the  $\gamma$ -rays from the radium contained in the lead cylinder D, they were 5 cm. and 5.5 cm. thick respectively. But since it is impossible to obtain perfect screening from  $\gamma$ -rays, there was a constant small leak in the chamber due to the rays which penetrated the lead blocks. F is an aperture of square section,  $3 \times 3$  cm.<sup>2</sup>, in the lead block B, its cross-section was made smaller when required by tightly packing its sides with suitable lead strips. A metal plate a few millimetres thick was placed at *e*, on top of the aperture, or at *d*, at the bottom of the aperture. This plate was the source of the secondary cathode radiation under investigation. The rays were deflected by means of a magnetic field, whose direction was at

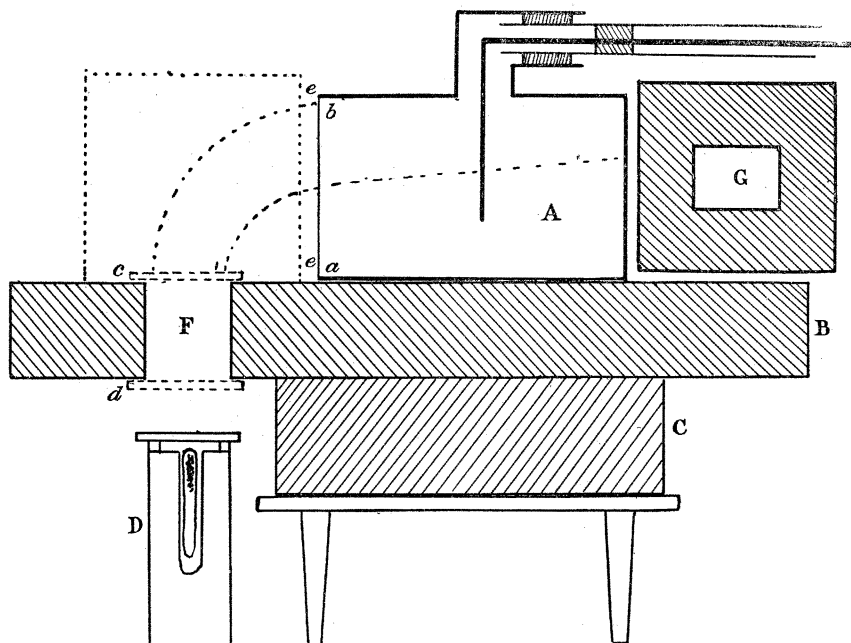


FIG. 2.

right angles to the plane of the paper, towards the tissue-paper window of the ionisation chamber A. The increase of leak in the chamber caused by the  $\beta$ -particles which penetrated into the chamber was measured for magnetic fields of different strengths. The position of the pole-pieces of the magnet (which were of square section) with respect to the other parts of the apparatus is indicated in the figure by a dotted square. The beam of cathode rays entering the chamber could be limited to any required size by placing at *e* a suitable lead stop of the form G.

First some experiments were made in order to see if previous screening of the  $\gamma$ -rays affects the velocity of the secondary rays. In one set of

experiments the radiating plate was placed at *c*, no stop of any kind being placed at *e*. Readings were taken with successively increased magnetic fields. The reading obtained with no magnetic field was subtracted from each of these readings, and the resulting values plotted against the current through the magnet. Fig. 3 shows some curves obtained in this way. They are the result of combining a large number of observations taken at different times. The sharp bends in the curves indicate the stage when the rays of

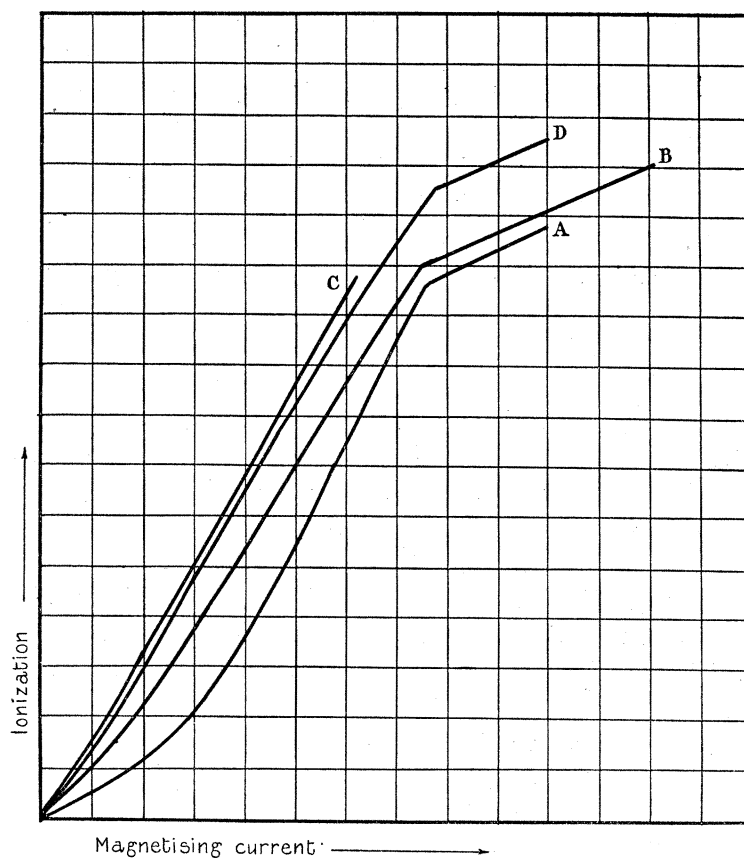


FIG. 3.

the outer edge of the principal stream of rays are deflected just sufficiently to enter the chamber. The curves have been so plotted that they are slightly separated from one another at the bends.

The curves A and B were obtained with a lead radiator. The  $\gamma$ -rays were sifted through lead screens of different thicknesses in the two cases, the curve A being obtained with a screen 1.5 cm. thick, and the curve B with

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a screen 3 mm. thick. The difference in the form of the curves indicates that the proportion of electrons moving with a velocity less than that corresponding to the bends in the curves, is decreased when the thickness of the lead screen is increased. A thick screen thus absorbs a greater proportion of the  $\gamma$ -rays which produce these slow electrons than a thin one. It appears, therefore, that the velocity of the secondary cathode radiation produced in a lead plate decreases with the absorbability of the  $\gamma$ -rays producing it.

The curves C and D were obtained with an aluminium radiator, using the same lead screens as before. The curve C corresponds to the thick screen, and the curve D to the thin screen being used. It will be seen that now there is scarcely any difference between the curves obtained. The previous passage of the  $\gamma$ -rays through a thick lead screen thus affects the more absorbable radiation from an aluminium plate to a less extent than that from a lead plate.

If part of the soft radiation from a plate is produced by the  $\gamma$ -rays that are selectively absorbed by the plate we would expect such a result. The substitution of a thick screen for a thin one would then affect the radiation from a plate of the same material as the screen to a greater extent than the radiation from a plate of some other material, for the  $\gamma$ -rays would be robbed in the first case to a greater extent of the rays most easily absorbed by the plate than in any other case. The rays that are most easily absorbed by a substance, it should be observed, are also the rays that are selectively absorbed by the substance, if selective absorption exists.

Two sets of readings were also taken in succession with a zinc screen 2 cm. thick and the thick screen of lead used previously, the radiator being of lead. Curves of the same form as A and B were obtained, the curve obtained with the lead screen being more convex towards the current axis than the curve obtained with the zinc screen. The lead screen thus robbed the beam of  $\gamma$ -rays of a greater proportion of the rays which produce soft cathode radiation from a lead plate than the zinc screen. This is in accordance with what we would expect according to the explanation given of the effect.

It should be observed that the soft rays dealt with in these experiments are of a much more penetrating character than those discussed in the previous section. The average range of the latter rays is so small that scarcely any of them could have entered the ionisation chamber in the experiments just described.

A large number of experiments were made under different conditions to make sure that the effects just described were not due to a disturbing

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influence of the radiation from other parts of the apparatus than that from the plate at *c*. Thus, readings were taken with the aperture F of different dimensions, and the pole-pieces at different distances apart; readings were also taken with the radiating plate placed at *d*. But in all cases a difference of the same nature as described was obtained between the curves for an aluminium and lead radiator when a thick and thin screen of lead were used. The difference in the curvature of the curves was, however, for two sets of experiments carried out under the same conditions, not always exactly of the same magnitude. This was probably due to hysteresis effects of the electro-magnet. The most consistent results were obtained when the radiating plate was placed at *d*. The reason for this appears to be that less of the very soft radiation, which would be greatly affected by the hysteresis of the magnet for small magnetic fields, entered the chamber in this case.

The conclusion, then, is that the velocity of the cathode radiation from a plate due to  $\gamma$ -rays decreases with the absorbability of the rays producing it.\* But the set of rays most easily absorbed by a substance need not necessarily be the same for all substances.

Some experiments by Innes† on the velocity of the secondary cathode rays produced by X-rays may be mentioned in this connection. This observer found that the velocity of the cathode radiation from a metal plate decreased with the softness of the X-rays producing it. He also found that, keeping the penetrating power of his X-rays constant, the velocity of the cathode rays was influenced by the nature of the radiating metal. The effect in the latter case is easily explained by selective absorption of the metals used. The set of rays best absorbed by a substance, not necessarily the same set for each substance, varied probably in degree of absorbability from substance to substance, and cathode rays of corresponding slowness were produced.

The bends in the curves in fig. 3 indicate, as already pointed out, that there is a principal stream of cathode rays from the radiating plate. If the rays were ejected from a plate in all directions we would scarcely obtain any indication of bends of any sharpness. The sharpness of the bends was found to depend somewhat, as we would expect, on the dimension of the aperture F, and the distance of the ionisation chamber from the aperture. This result confirms the deduction which Prof. Bragg and Dr. Madsen‡

\* Prof. Bragg and Dr. Madsen, according to a paper that has just appeared in the 'Phil. Mag.' of December, 1908, p. 918, have obtained the same result, but by a different method.

† 'Roy. Soc. Proc.,' A, vol. 79 (1907), p. 442.

‡ *Loc. cit.*

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made from some of their experiments on secondary radiation, namely, that the secondary cathode rays produced by the  $\gamma$ -rays are ejected in the direction of propagation of the rays.

An attempt was also made to determine absolutely the velocity of the fast-moving rays from a plate. But it had to be given up on account of the great heterogeneousness of the rays. The maximum velocity of a pencil of rays was found to depend on the size of the aperture F, and on the size of the aperture of the stop G placed at  $e$ , as we should expect if the rays are heterogeneous. And to obtain the relation between the velocity and amount of radiation, as has been done for the  $\beta$ -rays of radium, the apparatus was altogether unsuitable. The rays were therefore compared as a whole with the  $\beta$ -rays from radium. The size of the aperture F in these experiments was 1.1 cm.<sup>2</sup> and the lead plate used as radiator was placed at  $e$ . A stop of the form G was placed at  $e$ , the size of its aperture being 1.3 cm.<sup>2</sup> A set of readings was first taken with the lead radiator for magnetic fields of different strengths in the same way as before. A set of readings was next taken with the screen over the radium and the lead radiator removed. A stream of  $\beta$ -rays from the radium now passed through the aperture F, and was deflected by the magnetic field towards the ionisation chamber. It should be observed that, if the secondary rays from the lead plate radiator were ejected in the direction of propagation of the  $\gamma$ -rays, the beams in the two cases were similar in respect to the direction of motion of the electrons.

The readings obtained in the two cases are plotted against the current through magnet in fig. 4. The curve E refers to the cathode rays from the lead plate, and the curve F to the  $\beta$ -rays from the radium. It may be mentioned in passing that a comparison of the magnetic field with current through magnet by means of an exploring coil and current indicator showed them to be approximately proportional to one another over the whole range of magnetic fields used in these experiments. The curves have been so plotted that they are only slightly separated from one another: actually the maximum leak for the  $\beta$ -rays was much greater than that for the secondary cathode rays. It will be seen that in both cases the maximum leak is obtained for approximately the same current through the magnet. The velocity of the secondary cathode rays from a lead plate exposed to the  $\gamma$ -rays is therefore, as a whole, the same as that of the  $\beta$ -rays of radium.

It will be interesting, without committing ourselves to any particular theory of the  $\gamma$ -rays, to see what this result means in the light of the two theories of the  $\gamma$ -rays at present put forward.

According to the theory of Prof. Bragg and Dr. Madsen, the  $\gamma$ -ray consists

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of a negative electron associated with a particle possessing an equal charge but of opposite sign, the combination forming a neutral pair of particles. In traversing matter, the pair is liable to get broken up, with the result that the negative particle proceeds onwards; the  $\gamma$ -ray now appears as secondary cathode radiation. A  $\gamma$ -ray is supposed to arise by an electron picking up a positive particle which it encounters in traversing matter.

Now, if the positive particle has an appreciable mass, the velocity of the pair of particles must be less than that of the negative electron before the pair was formed. Consequently, when the pair is stripped of its positive particle, the velocity of the cathode ray proceeding onwards should be

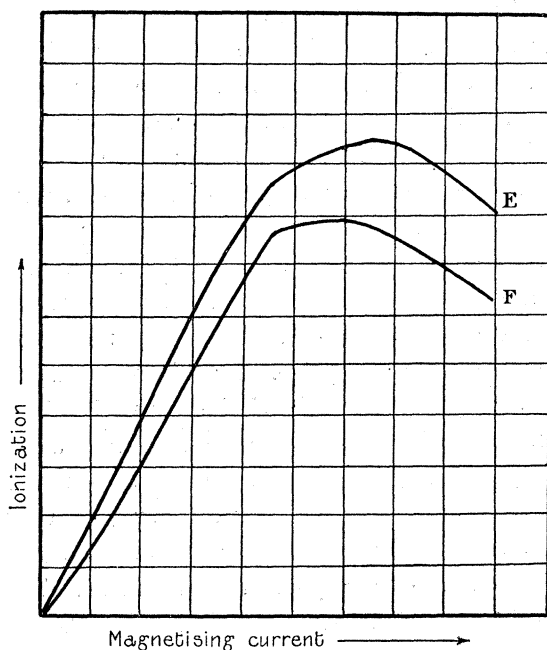


FIG. 4.

smaller than its velocity before association with the positive particle. If, for example, the mass of the positive particle is equal to that of the negative, the velocity of the secondary cathode radiation should be about  $1/\sqrt{2}$ , or about 0·7 of that of the  $\beta$ -rays of radium. In that case the maximum for the curve for the secondary cathode rays in fig. 4 would be almost half-way between the zero and the maximum for the  $\beta$ -rays of radium. But since the curves show that the velocities are practically the same, it follows that the positive particle (if the neutral pairs are formed in the way described) must be small in comparison with that of the negative.

If the mass of the positive particle is entirely electrical, it follows from the

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well-known equation  $m = \frac{2}{3} \frac{e^2}{a}$ , which connects the electrical mass with the charge and radius of particle, that the radius of the positive particle must be large in comparison with that of an electron. This condition would be approximately fulfilled by a positive particle the diameter of which is equal to that of a molecule, but whose mass is entirely electrical.

On the æther-pulse theory of the  $\gamma$ -rays in its usual accepted form, the pulse is supposed to spread out in the form of a spherical shell with the generating electron as centre. If the energy of an electron ejected by a  $\gamma$ -pulse is derived entirely from that of the pulse, its energy can only be a small fraction of that of the pulse, and therefore of that of the electron which generated the pulse. But this is contrary to experience.

To overcome this difficulty, Prof. J. J. Thomson proposed a modified æther-pulse theory.\* According to this theory, the pulse is supposed to proceed in one direction only from the radiating electron, and that the area of the wave front of the pulse remains constant as the distance of the pulse from the electron increases. The electron ejected by a pulse is therefore able to absorb the whole energy of the pulse; and if the whole energy of the radiating electron is transformed into pulse energy, the velocity of the secondary electron may be equal, or at least very nearly equal, to that of the electron which produced the pulse. Prof. Thomson also suggested that the wave front of a ray of light may be similarly restricted.

It will be interesting in this connection to obtain an estimate of the thickness of a  $\gamma$ -ray pulse. If a ray of light and a  $\gamma$ -pulse are identical in structure the interesting experiments of Ladenburg† on the velocity of the cathode rays ejected by ultra-violet light furnish data from which an estimate of the thickness of a  $\gamma$ -pulse may be made. This experimenter found that the product of the velocity of a beam of secondary cathode rays into the wave-length of the ultra-violet light producing it is constant. An approximate value of this constant for our purpose is obtained by taking the velocity  $2 \times 10^7$  cm./sec. for the cathode rays (a value found by Lenard) to correspond to the wave-length  $288 \mu\mu$  of ultra-violet light. Therefore, if  $\lambda$  denotes the thickness of a  $\gamma$ -pulse, and we take the velocity of the  $\beta$ -rays as  $2.5 \times 10^{10}$  cm./sec., we have  $\lambda 2.5 \times 10^{10} = 218 \mu\mu \times 2 \times 10^7$ , or  $\lambda = 174 \mu\mu \times 10^{-3}$ . From the last equation it will be seen that the thickness of a  $\gamma$ -pulse is about one-thousandth of the wave-length of ultra-violet light. And since the wave-length of ultra-violet light is about one

\* 'Camb. Phil. Soc. Proc.,' vol. 14, part 4, p. 417.

† 'Verh. der Deut. Phys. Gesellschaft,' 1907, p. 507.

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thousand times the diameter of a molecule, the thickness of a  $\gamma$ -pulse is about equal to the diameter of a molecule.

*Summary.*

Part of the cathode radiation from a plate exposed to the  $\gamma$ -rays of radium consists of very soft rays which are absorbed in 1 or 2 cm. of air.

The softness of the radiation is practically independent of the thickness of the radiator, and previous sifting of the  $\gamma$ -rays through a thick screen.

The radiation appears to be considerably softer on the side of the radiating plate where the  $\gamma$ -rays emerge than on the side where they enter.

Measurements of the softness of the radiation for radiators of different materials on the side where the  $\gamma$ -rays entered showed that it is practically independent of the nature of the material of the radiator.

The soft radiation produced by the  $\beta$ - and  $\gamma$ -rays of radium together is of a more penetrating character than that produced by the  $\gamma$ -rays alone.

The penetrating cathode rays produced directly by the  $\gamma$ -rays have been shown to possess different velocities. It was found that the penetrating power of the cathode radiation from a plate decreases with the increase of absorbability of the  $\gamma$ -radiation which produces it.

The velocity of these secondary rays as a whole is, as a first approximation, equal to that of the  $\beta$ -rays of radium.

It gives me great pleasure to thank Prof. Thomson for his interest and advice during this research.

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*Electrolytes and Colloids.—The Physical State of Gluten.*

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